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Citation for published version (APA):

Document status and date:
Published: 01/01/1990

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Measurements of the dynamic stiffness of modular milling tools

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WPA Report 0840  january 1990

SUMMARY

With the growing use of flexible manufacturing systems, also the use of a flexible tool–system is rising. Recently a number of new systems for milling and boring operations are developed. To compare the different designs ten different makes of modular boring tools, with a length of ± 200 and ± 300 mm, have been tested dynamically.

As a result the dynamic stiffness, the resonance frequency and the damping are given in relation with the length and mass of the tool. From these results a first selection for a modular tool can be made.
INTRODUCTION.

In modern production flexibility is an important topic. In order to obtain a flexible production system, the tooling of the manufacturing cells must be extensive and easy to change. Especially for the less used diameters and greater depths it is not useful, and expensive, to keep special tools in stock. In these cases it is usual to use a modular tooling system. Out of a great number of components a tool can be composed.

One can distinguish two clamping and locking systems in the available modular tooling systems, the central and radial approachable systems. The disadvantage of a central clamping system is the fact that one has to disassemble the complete tool in order to mount a new tool–head on the tool or to lengthen or shorten the tool. In the past years several new systems, in which the parts individually can be mounted or demounted, have been developed. Most of these systems have radial (approachable) clamping devices.

The question arises which of the systems to choose for a flexible machining system and/or the workshop. Next items are of interest in the process of selection:

- availability
- number of different elements/tools
- ease of assembly
- reproductiveness
- static stiffness
- dynamic stiffness
- price

Of these items the aspect of dynamic stiffness is dealt with in this report.

SELECTION OF MODULAR TOOLING SYSTEMS.

The machines we have the tooling systems selected for are CNC machining centres with a spindle based on taper
For most modular tooling systems based on this taper, the standard shaft diameter $D = 50$ mm. With $l_{\text{max}} = 6 \times D$ the maximal tooling length becomes about 300 mm. For one of the machining centers this length even was exceeding the allowable length in the magazine. Because of the common use of smaller lengths it was decided to do dynamic measurements for the tool-lengths of 200 and 300 mm. Due to interests and availability the makes noted in Tabel 1 were selected. For all of these systems it is possible to mount and demount all of the assembly parts separately.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>System</th>
<th>Make</th>
<th>Clamping principle</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CO</td>
<td>SGIP</td>
<td>axial - symmetric</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>URMA</td>
<td>axial - symmetric</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>ABS</td>
<td>KOMET</td>
<td>radial - symmetric</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>Flexibore</td>
<td>KELCH</td>
<td>radial - symmetric</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>Modulock</td>
<td>BAHMÜLLER</td>
<td>radial - symmetric</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>Varilock</td>
<td>SANDVIC</td>
<td>radial - symmetric</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>Variobore</td>
<td>HERTEL</td>
<td>radial - symmetric</td>
<td>50</td>
</tr>
<tr>
<td>8</td>
<td>CKB</td>
<td>KAISER</td>
<td>radial - asymmetric</td>
<td>50</td>
</tr>
<tr>
<td>9</td>
<td>Graflex</td>
<td>EPB</td>
<td>radial - asymmetric</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>Multibore</td>
<td>WOHLHAUPTER</td>
<td>radial - asymmetric</td>
<td>50</td>
</tr>
</tbody>
</table>

Tabel 1. The selected modular tools

Examples of these clamping principles are illustrated in the figures 1 – 3. The composition for two different tools are shown in Fig. 4.
Fig. 1. axial (SGIP)

Fig. 2. radial-symmetric (HERTEL)

Fig. 3. radial-assymetric (KAISER)
MEASUREMENT SETUP.

Because of the ease of measuring, the first measurements of the dynamic stiffness were carried out on a horizontal machining centre. Studying the results of the modal analysis, it was questionable what was measured, the stiffness of the tool or the stiffness of the main-spindle of the machine. It was decided to build a special measuring device on which the tools could be mounted and measured. The measuring device is a solid block in which a ring with calibrating taper (ISO 40) was fixed. The measuring device itself was mounted on a heavy machine-bed. Although
normally the tools are pulled into the taper of the machine-spindle, in the measuring device the tools are pushed in the taper by two force-calibrated fixing bars pushing on the tool flange (Fig. 5). The total pushing force is 10500 N, the same as used in the machining centres.

In behalf of modal analysis of the modular tools, a model of the tool and fixture was made (Fig. 6). For geometrical reasons on all tools the accelerometer was placed about 25 mm below the top of the tool. The tool-bar itself was excited on 8 and the fixture on 4 points, this to control the stiffness of the fixture and bed. Pulse excitation by hammer was used to measure the transfer functions between accelerometer and excitation point.

Extensive tests with two different tools were carried out in order to study the sensitivity to excitation- and fixing-direction. Small differences were found, but of insufficient
Fig. 6. The model of a tool with measuring points

importance to measure all the tools in that way. Therefore it was decided to excite the tool only in X- and the fixture in Z-direction.

MEASUREMENT RESULTS

As an illustration, in Fig. 7 the transfer function of the top of tool 10 (Wohlhaupter), with a length of 221 mm, is given. The principle mode for this tool is given in Fig. 8. As can be seen, the tool is almost moving as a stiff bar rotating around the top of the calibrating ring. In this way it seems that the taper itself is the weakest part of the system, and not the main spindle of the machine, as was suggested before. To test the influence of the clamping force on the
Fig. 7. The transfer function of tool 10 (length 200), clamped with different forces

Fig. 8. The principle mode of tool 10 (length 200 mm)
dynamic stiffness, this force was doubled to 21000 N. The results of these measurements are listed in Tabel 2.

<table>
<thead>
<tr>
<th>Force (N)</th>
<th>Flexibility (µm/N)</th>
<th>Frequency (Hz)</th>
<th>Damping (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10500</td>
<td>1.8</td>
<td>564</td>
<td>2.6</td>
</tr>
<tr>
<td>21000</td>
<td>1.9</td>
<td>599</td>
<td>2.3</td>
</tr>
</tbody>
</table>

**Tabel 2. Influence of the clamping force**

So clamping with a higher force does result in a higher static stiffness of the tool, as can be seen on the higher resonance frequency. Due to lesser damping in the taper, the dynamic stiffness is decreasing, resulting in a higher flexibility of the tool.

The results of the modal analysis of all tools are compiled in **Tabel 3** for the tools with a length of about 200 mm, and in **Tabel 4** for the tools with a length of about 300 mm. Because of the fact that not all tools have the same length and composition, the factor \( \sum (l \cdot M) \) is introduced as a length and weight factor.

<table>
<thead>
<tr>
<th>Tool Nr.</th>
<th>Length (mm)</th>
<th>Flexibility (µm/N)</th>
<th>Frequency (Hz)</th>
<th>Damping (%)</th>
<th>( \sum (l \cdot M) ) (Kg.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>215</td>
<td>1.7</td>
<td>570</td>
<td>3.7</td>
<td>297</td>
</tr>
<tr>
<td>2</td>
<td>205</td>
<td>5.0</td>
<td>714</td>
<td>0.9</td>
<td>212</td>
</tr>
<tr>
<td>3</td>
<td>218</td>
<td>1.2</td>
<td>512</td>
<td>2.2</td>
<td>350</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>1.9</td>
<td>781</td>
<td>1.7</td>
<td>216</td>
</tr>
<tr>
<td>5</td>
<td>230</td>
<td>1.7</td>
<td>513</td>
<td>2.2</td>
<td>330</td>
</tr>
<tr>
<td>6</td>
<td>224</td>
<td>2.1</td>
<td>431</td>
<td>2.2</td>
<td>400</td>
</tr>
<tr>
<td>7</td>
<td>230</td>
<td>1.7</td>
<td>451</td>
<td>2.0</td>
<td>431</td>
</tr>
<tr>
<td>8</td>
<td>215</td>
<td>1.1</td>
<td>517</td>
<td>2.6</td>
<td>344</td>
</tr>
<tr>
<td>9</td>
<td>218</td>
<td>2.2</td>
<td>445</td>
<td>2.4</td>
<td>369</td>
</tr>
<tr>
<td>10</td>
<td>221</td>
<td>1.6</td>
<td>564</td>
<td>2.6</td>
<td>318</td>
</tr>
</tbody>
</table>

**Tabel 3. Results for a tool—length of 200 mm**
<table>
<thead>
<tr>
<th>Tool Nr.</th>
<th>Length (mm)</th>
<th>Flexibility (μm/N)</th>
<th>Frequency (Hz)</th>
<th>Damping (%)</th>
<th>$\Sigma(I \cdot M)$ (Kg.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>287</td>
<td>7.0</td>
<td>345</td>
<td>1.1</td>
<td>517</td>
</tr>
<tr>
<td>2</td>
<td>307</td>
<td>5.8</td>
<td>332</td>
<td>1.9</td>
<td>466</td>
</tr>
<tr>
<td>3</td>
<td>283</td>
<td>3.6</td>
<td>334</td>
<td>1.5</td>
<td>587</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>7.0</td>
<td>375</td>
<td>1.1</td>
<td>518</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>3.4</td>
<td>334</td>
<td>1.7</td>
<td>576</td>
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<tr>
<td>6</td>
<td>305</td>
<td>8.5</td>
<td>275</td>
<td>1.2</td>
<td>600</td>
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<tr>
<td>7</td>
<td>290</td>
<td>2.6</td>
<td>290</td>
<td>4.1</td>
<td>674</td>
</tr>
<tr>
<td>8a</td>
<td>305</td>
<td>11.5</td>
<td>273</td>
<td>0.9</td>
<td>709</td>
</tr>
<tr>
<td>8b</td>
<td>305</td>
<td>5.5</td>
<td>278</td>
<td>1.7</td>
<td>709</td>
</tr>
<tr>
<td>9</td>
<td>318</td>
<td>12.0</td>
<td>238</td>
<td>1.3</td>
<td>769</td>
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<tr>
<td>10</td>
<td>321</td>
<td>4.4</td>
<td>282</td>
<td>1.8</td>
<td>625</td>
</tr>
</tbody>
</table>

**Table 4. Results for a tool—length of 300 mm**

In Table 4, for tool 8 two results are given. For 8a an element of 90 mm was placed on top of two elements of 60 mm, for 8b the two elements of 60 mm were placed on top of the element of 90 mm. From these two measurements it is clear that also the position of the elements can be of influence on the dynamic result, tool 8b has a higher damping which results in a lower flexibility. This is shown in Fig. 8 where the transfer functions for the tools 8a and 8b are given.

In Fig. 9 the transfer functions and in Fig. 10 the principle modes of tool 4 (KELCH), for both the lengths of 200 and 300 mm, are given as an illustration.

The drawings of the measured tools and the corresponding transfer functions of the top of the tools are given in the appendix.
In Fig. 11 the (dynamic) flexibility for the different tools is given as a function of $\Sigma(l \cdot M)$. To distinguish the different types of clamping, for each group a different type of line is used.

From the dynamic flexibility and the corresponding damping the 'static' flexibility can be calculated, the results are given in Fig. 12.

Fig. 8. The transfer functions of tool 8a and 8b
Fig. 9. The transfer functions of tools 4 (KELCH)

Fig. 10. The principle modes of tools 4 (KELCH)
Fig. 11. The dynamic flexibility of the tools

Fig. 12. The 'static' flexibility of the tools
CONCLUSION

From the graphs in Figs. 9 and 10 can not be proved that a certain clamping principle is the best, although the overall results of an axial–symetric principle are less good. Only looking at the dynamic flexibility, the result for tool 3, 5 and 7 are the best. Keeping the 'static' flexibility in mind one will prefere the tool–system 3 (ABS–Komet) and 5 (Modulock–Bahmüller).

From the graphs is very clear that especially for the longer tools the differences in dynamic flexibility can be great, but, as mentioned in the introduction, flexibility of a tool is only one aspect of choosing a system.
The transfer functions of tool 1
Tool 2: URMA

The transfer functions of tool 2
Tool 3: ABS–KOMET

The transfer functions of tool 3
Tool 4: Flexibore–KELCH

The transfer functions of tool 4
Tool 5: Modulock—BAHMULLER

The transfer functions of tool 5
Tool 6: Varilock—SANDVIC

The transfer functions of tool 6
Tool 7: Variobore–HERTEL

The transferfunctions of tool 7
Tool 8: CKB–Kaiser

The transfer functions of tool 8
The transfer functions of tool 9
Tool 10: Multibore—WOHLHAUPTER

The transfer functions of tool 10